PHASE TRANSFER FOR RADIO ASTRONOMY INTERFEROMETERS, OVER INSTALLED FIBER NETWORKS, USING A ROUND-TRIP CORRECTION SYSTEM

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Abstract

The MERLIN telescope, based at Jodrell Bank, achieves coherent operation using a frequency standard transmitted over microwave links. This system is locally known as the 'L-band Link' (LBL). The LBL uses pulses of RF carrier waves to transmit bi-directionally between two locations in a time-division-multiplexed system (TDM). Tests in the laboratory and astronomical observations have confirmed that the LBL detects changes of delay at approximately the 1-picosecond level over periods of time extending to many hours.

The legacy, radio-based, LBL terminal equipment was adapted to transmit, using thermally controlled externally modulated lasers at 1550 nm, over an installed fiber network of up to 110 km. The TDM operation of the LBL means that the system lasers may have very close wavelengths and are transmitted over a single fiber. Phase errors due to chromatic dispersion, circulator leakage, and differences in fiber path length are, therefore, reduced or eliminated. The round-trip delay value, halved, and the one-way path delay were measured. Any differences between the two values will indicate the error in the delay measurement, or stability, of the LBL. The objective was to establish if, in an LBL over-fiber system, an rms error close to the 1-picosecond level could be achieved.

The measured rms error of the LBL over-fiber system is 1 picosecond, over sampling intervals of between 1 second and 1 minute, irrespective of fiber length. This suggests that the short-term instability seen in the results is due to terminal equipment and measurement error, rather than a fiber effect. Over a 2-hour sampling interval, an LBL over 110-km fiber system has an rms error of 4 picoseconds, compared to the legacy terminal equipment that has an rms error of 3 picoseconds, over the same period.

These findings are encouraging and indicate that a fiber-based LBL system can achieve the stabilities required for radio astronomy observations at 22 GHz. A fiber-based system for local oscillator transfer has applications in future fiber-linked radio astronomy interferometers, such as e-MERLIN and the Square Kilometre Array.

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INTRODUCTION

Modern radio interferometers require highly synchronous observations of data from antennas at diverse locations. The local oscillator (LO) frequency standards used in these systems have to be very stable. For radio astronomy at 22 GHz, the local oscillator phase should be stable to 8° (1 ps equivalent) in 1 second. There is a motivation to utilize fiber-based links for transferring local oscillator phase to outstations of a radio telescope in order to use infrastructure efficiently and save money.

This paper provides details of an experiment, conducted at Jodrell Bank Observatory, to measure changes in the one-way and round-trip transport delay of a 1.5-GHz signal transmitted over 110 km of installed standard single-mode fiber. This work is applicable to both the Square Kilometre Array (SKA) telescope and also to e-MERLIN (UK-based multi-element radio linked interferometer).

COHERENT OPERATIONS USING A LEGACY SYSTEM

The MERLIN telescope, based at Jodrell Bank, achieves coherent operation using a frequency standard transmitted over microwave links. This system is locally known as the ‘L-band Link’ (LBL). The system both maintains coherence of the array and continuously measures changes in the time-of- flight delay of the data transmission microwave links from each antenna.

A Sigma-Tau hydrogen maser source provides the frequency standard. Pulsed 1.5-GHz signals are transmitted, 88 times per second, to each outstation. In order to avoid confusion between the L-band link systems of different outstations, they are allocated different pulse lengths. Terminal equipment at the outstations contains excellent-quality crystal oscillators that use the 1.5-GHz signal to lock a 5-MHz frequency standard. Software records the difference in the go and return phase values and keeps a record the round-trip phase ($\Phi_{\text{round trip}}$). This value, halved, gives information on changes in the phase delay of data transmitted from the outstation to Jodrell Bank over the microwave links. It is fed into the MERLIN correlator as a correction between data from the different outstations before correlation. This round-trip correction system relies on the reciprocity of the phase delay in the go and return transmission paths.

The L-band Link system has been working reliably for over 20 years **[1]**. However, with the advent of a fiber network upgrade to MERLIN, there is a motivation to use the fiber network and reduce the costs associated with the microwave links. In addition, microwave links are not considered practical for the SKA, where the concentration of antennas would create unacceptable complexity and produce interference in the radio astronomy. Transmissions in an optical fiber suffer dispersion, but the techniques used in the LBL might offer the prospect of a comparable accuracy over fiber, provided that similar-enough optical wavelengths are used in the two directions. The pre-existing, radio-based LBL system was adapted to measure changes in the round-trip delay in installed fiber of up to 110 km long. The objective was to establish if, in an LBL over-fiber system, reciprocity would still apply.

SYSTEM REQUIREMENTS

The L-band link has two tasks:

- Transfer a pulsed 1.5-GHz LO frequency standard to the outstations
- Provide information on the phase delay of data from the outstations.

Any fiber-based L-band link will have to fulfill both of these functions reliably.

The specification for radio astronomy at 22 GHz with e-MERLIN is that the fiber link should be reciprocal to:

- Within 1 ps over a 1-second timescale (equivalent to 8º of phase at 22 GHz) – this is to keep signal loss at less than 1% over timescales less than a typical correlator integration period.
- 2 ps over timescales of 1 minute, to keep coherence loss to a few percent whilst integrating on a calibration source.
- 10 ps over a timescale of 10 minutes in order to maintain the linear phase variation between calibrator points.

Other methods of time transfer exist, such as GPS **[2]** and Two-Way Satellite Time Transfer **[3]**. However, neither method can meet the stringent specifications required by high-frequency radio astronomy. The specifications are concerned with not just the amplitude of changes in the system, but the speed of that change. Large changes can be corrected if they occur slowly over time. It is the amplitude of fast changes which are of particular concern here.

The design should use the most cost-effective laser devices possible to achieve these specifications. The 1550-nm electro-absorption modulated lasers (EML) used in this study have an integrated external modulator with thermal control delivered by a thermoelectric cooler (TEC). The use of 1310-nm lasers at the dispersion minima of fiber was discounted because of the transmission distances between antennas. The performance of directly modulated 1550-nm lasers with no thermal control has been examined previously and published **[4]**. The maximum span of fiber in the e-MERLIN network is 120 km, between the Knockin telescope and a repeater site at Birmingham. A fiber LBL will need to transmit reliably over this distance. In this experiment, 110 km of installed fiber was used to simulate the transmission distance required of the system. The fiber link was arranged in a loop, so that both ends terminated at equipment in the laboratory.

FIBER TRANSMISSION

Optical fibers provide a low-loss medium for the transport of light over a large frequency range. The ability to transport light over great distances at very high data rates makes optical fiber an ideal medium for the transport of information **[5]**. The light propagates along the fiber by the process of total internal reflection, and is contained in the glass core and cladding by careful design of their geometry and refractive indices. The fiber used in the installed links of the e-MERLIN network is single-mode G.652 fiber. 1310-nm lasers were not used in this experiment, although at the dispersion minima of fiber, they experience a higher attenuation and will not cover the 120-km distances required for the e-MERLIN system. 1550-nm lasers experience low attenuation (0.25 dB/km) and are suitable for longer distance transmission.

The transit delay of an optical signal through a fiber cable will be affected by the dispersive properties of the fiber and the thermal expansion of the fiber with temperature. A round-trip correction system can remove the effects of thermal expansion if the transmission path is reciprocal. Optical fiber is an anisotropic material, which means that light incident upon it will split into two orthogonal polarisations that travel at different speeds. The fast and slow axis of the fiber will change according to differences in dimensions, strain, and temperature. It is impossible to predict over a long length of fiber how the polarization will change and which path the light might take. This means that optical fiber is not reciprocal. This phenomenon manifests itself in high-speed digital networks as polarization-mode

dispersion. The experiment detailed in this paper was designed to see the degree to which this non-reciprocity effects a phase-delay measurement, or whether the effect is so small it can be considered negligible for our purposes.

At 1550 nm, the chromatic dispersion in standard single-mode fiber is 17.35 ps/nm/km. This indicates that the wavelength stability of the system terminal lasers will have a significant impact on the transit delay of the optical signal through the fiber cable. If the terminal lasers drift, then the reciprocity assumption will not hold and this will affect the phase stability of the system.

LASER WAVELENGTH STABILITY

The system specifications require the LBL to be stable to:

- 1 ps in 1 second,
- 2 ps in 1 minute, and
- 10 ps in 10 minutes.

These specifications set the requirement for the wavelength stability $\Delta\lambda$ of the laser sources at 1550 nm over time. A value of $\Delta\lambda$ can be calculated using the equation below **[6]**:

$$\Delta\lambda = \frac{\Delta\tau}{DL}$$

Using a value of dispersion *D* (1550 nm) = 17.35 ps/nm/km and a maximum link length *L* of 110 km, then:

- over 1 second, the two system lasers should have wavelengths stable within 0.52 pm or 65 MHz of each other
- over 1 minute, the two system lasers should have wavelengths stable within 1.05 pm or 130 MHz of each other
- over 10 minutes, the two system lasers should have wavelengths stable within 5.24 pm or 649 MHz of each other.

Second-order effects, such as the change in fiber dispersion with temperature and additional dispersion due to thermal expansion, are negligible.

Both EML devices used in this experiment had specified central wavelengths of 1542.1 nm (Channel 44 on the ITU Grid). An initial look at the stability requirements of the LBL suggests that commercially available EML devices will not meet these requirements. However, it is important to note that, since the wavelength drift is predominately a temperature effect, and since temperature will vary slowly over time, this will dampen the wavelength drift of the lasers. In addition, the wavelength stability specifications for the LBL fiber apply to two laser wavelengths *relative* to one another. It is, therefore, possible for laser wavelengths to drift, so long as the wavelengths remain locked to within the tolerated wavelength separation. The wavelength stability of lasers is affected predominately by case temperature, and those lasers that are temperature controlled will have a more stable wavelength output than those that are not **[7]**. The behavior of a temperature-controlled laser wavelength, over short timescales, is governed by the integrity of the feedback loop that controls the laser TEC. Most TEC control loops are capable of controlling the temperature to 0.1 ºC and the laser wavelength changes with temperature by 0.1 nm/ºC. The laser wavelength change will be a slow change (of the order of 10s of seconds) governed by case temperature, rather than a rapid fluctuation. In the case where lasers are on a bench in the lab, the

ambient temperature will change by only a few degrees over a 24-hour period and the laser wavelength change due to temperature is predicted to be slow and small. In an operational system, the lasers can be placed in a controlled environment to prevent fast changes in case temperature and further reduce any wavelength drifts.

EXPERIMENTAL METHOD

The experiment used existing L-band link terminal equipment connected to optical transmitters and receivers separated by optical circulators and a fiber link of variable length. Figure 1 shows the experimental setup. Thermally controlled Photonic Systems, Inc., 1550-nm optical links (Part # PSI-1600) with matching optical receivers were used in the experiment. The master had a specified central wavelength of 1542.1 nm (measured value = 1542.176 nm) and the slave laser had a specified central wavelength of 1542.1 nm (measured value = 1542.862 nm).

A pulsed 1.5 GHz signal, locked to the maser, was sent from the Master L-band link over RF cable, via a circulator and attenuator, to an optical transmitter. This laser was assigned as the master laser for the system. The signal was then transmitted, via an optical circulator, over a link of 110 km of installed optical fiber. The optical fiber used is part of the e-MERLIN network and is, in part, buried and, in part, laid in troughs along the railway lines. An optical circulator at the end of the link separates a Slave receiver and a Slave transmitter. The Slave receiver took the signal sent from the Master laser and converted it to an RF signal, which was connected to an aerial switch on a Slave L-band link unit. This was described as the ‘go’ path of the signal.

The oscillators in the slave L-band link unit locked to the received signal and then switched the locked signal to the output. The output of the Slave L-band link unit was connected, via attenuators, to another laser. This laser was assigned as the slave laser for the system. The pulsed 1.5-GHz signal was then sent back over the same link of fiber via the optical circulator. At the other end of the fiber link, the signal was detected by a master receiver and converted to an RF signal. This RF signal was connected to the Master L-band link. This was described as the ‘return’ path of the signal. There was no interference between the ‘go’ signal and ‘return’ signal, because they are transmitted over the link at different times.

A link with no optical components or fiber was used to establish the instability error in the LBL equipment and the measurement setup. This was called the ‘Back to Back’ link. By using only RF components in the system, this measurement shows the error floor of the measuring system.

The Master L-band link converts the ‘go and return’ signals into a measurement of round-trip phase ($\Phi_{\text{round trip}}$). A one-way trip delay ($\Phi_{\text{one way}}$) was measured using a HP 8508A vector voltmeter connected to both the Master and Slave L-band links at 499.9 MHz. If the ‘go’ and ‘return’ paths are reciprocal, then any changes in path delay of one will be experienced in the other and the value:

$$(\Phi_{\text{round trip}} /2) - \Phi_{\text{one way}} = 0.$$

Any error in this assumption will be reproduced as an error in the correction added to the astronomical data at correlation. The Allan variance (σ_y^2) of this error was calculated using the equation for time sampled series. Where x_i is taken from a set of M+1=N discrete time deviation measurements between a pair of oscillators and τ is sample time **[8]**:

$$\sigma_y^2(\tau) \approx \frac{1}{2\tau^2(M-2n+1)} \cdot \sum_{i=1}^{M-2n+1} \left(x_{i+2n} - 2x_{i+n} + x_i\right)^2$$

The square root of the Allan variance (Allan deviation value, σ_y) was plotted. The rms stability of this error value was calculated by multiplying the Allan deviation by the sample time period of interest, i.e.

$$\sigma(\tau) = \tau\sigma_y .$$

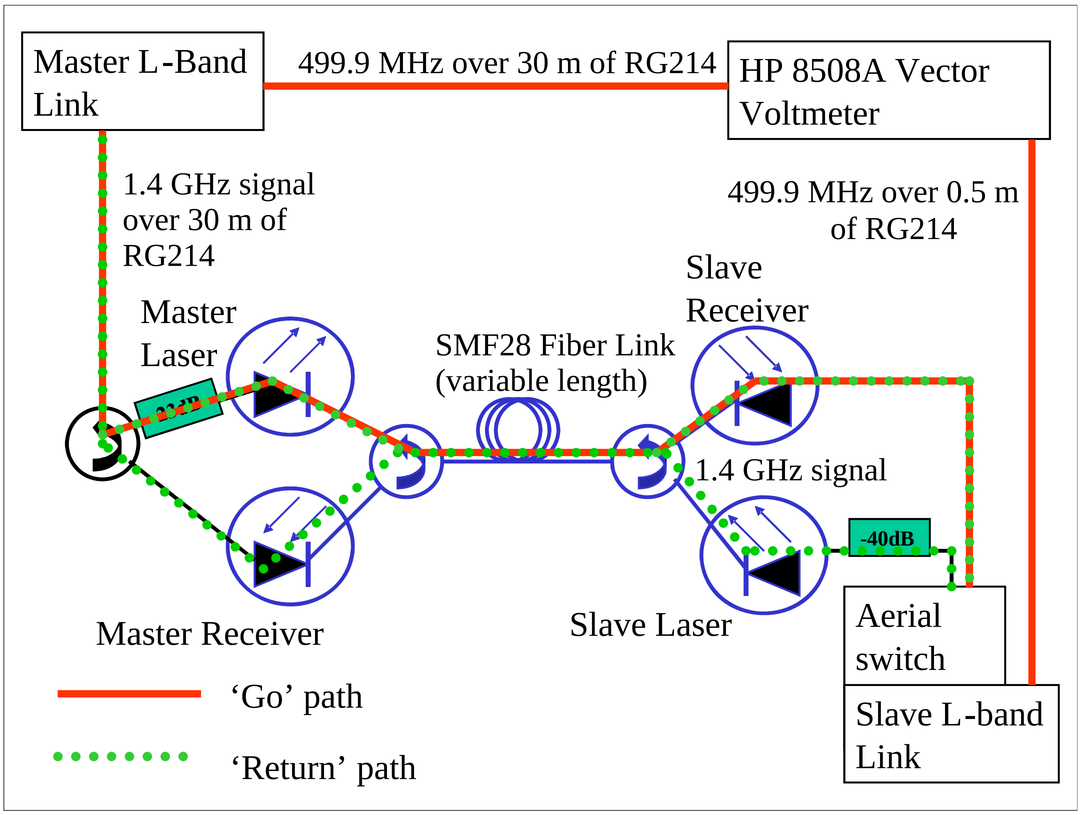

Figure 1. Experimental setup.

RESULTS

Figure 2 shows an Allan deviation plot for the Back to Back measurements. This is the error floor of the existing LBL system, measured using the equipment described here.

The experiment was repeated using the thermally controlled 1550-nm lasers and a 110-km link of fiber. The Allan variances for a signal transmitted one-way and the round-trip corrections were calculated and an Allan deviation plot produced. These were compared with the Allan deviation plot of the Back to Back measurements, shown in Figure 2. The Allan deviation plot shown in Figure 3 indicates that a long fiber link, using thermally controlled lasers, is as stable as the Back to Back link. The need for a round-trip correction system for long-distance links can be seen on the plot, where the stability of the one-ay phase, detected directly and with no round-trip correction, is clearly out of specification by a factor of 2.

The rms phase stability of the round-trip correction system was calculated. Figure 4 shows the difference between the results found in the Back to Back measurement and the 110-km fiber link, when compared with the system specifications.

The rms phase stability plot shows that the LBL system, as measured using a Back to Back system with no optics, has:

- a 1 ps stability over 1 second,
- a 2 ps stability over 1 minute,
- a 3 ps stability over 10 minutes, and
- a 3 ps stability over 2 hours.

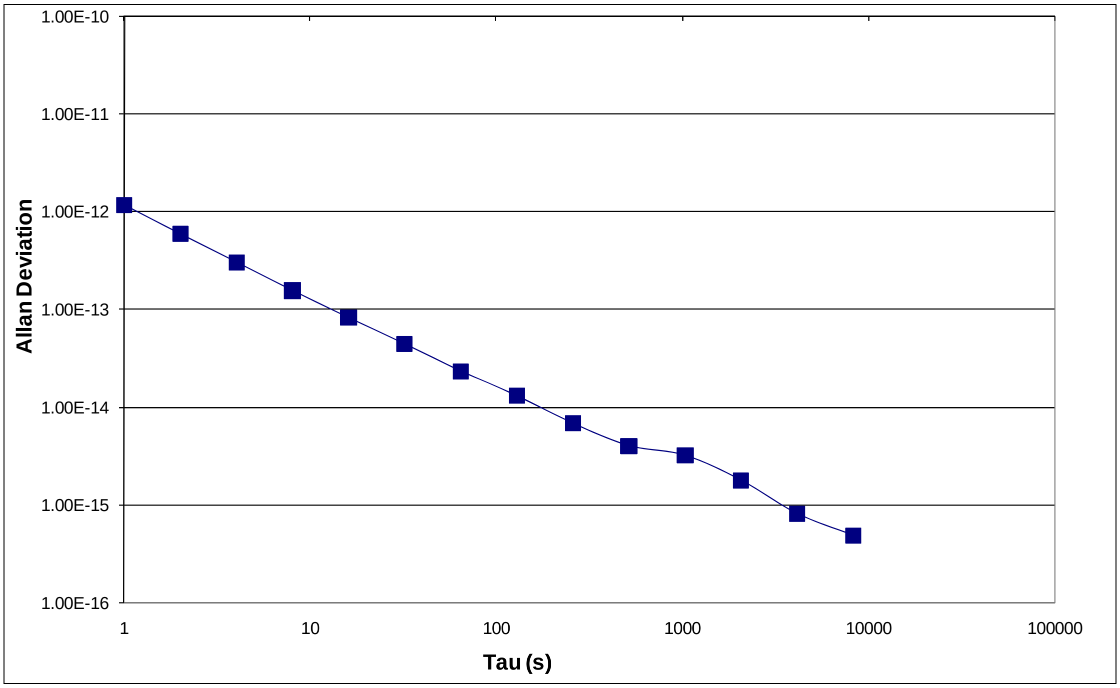

Figure 2. Allan deviation plot for a Back to Back measurement.

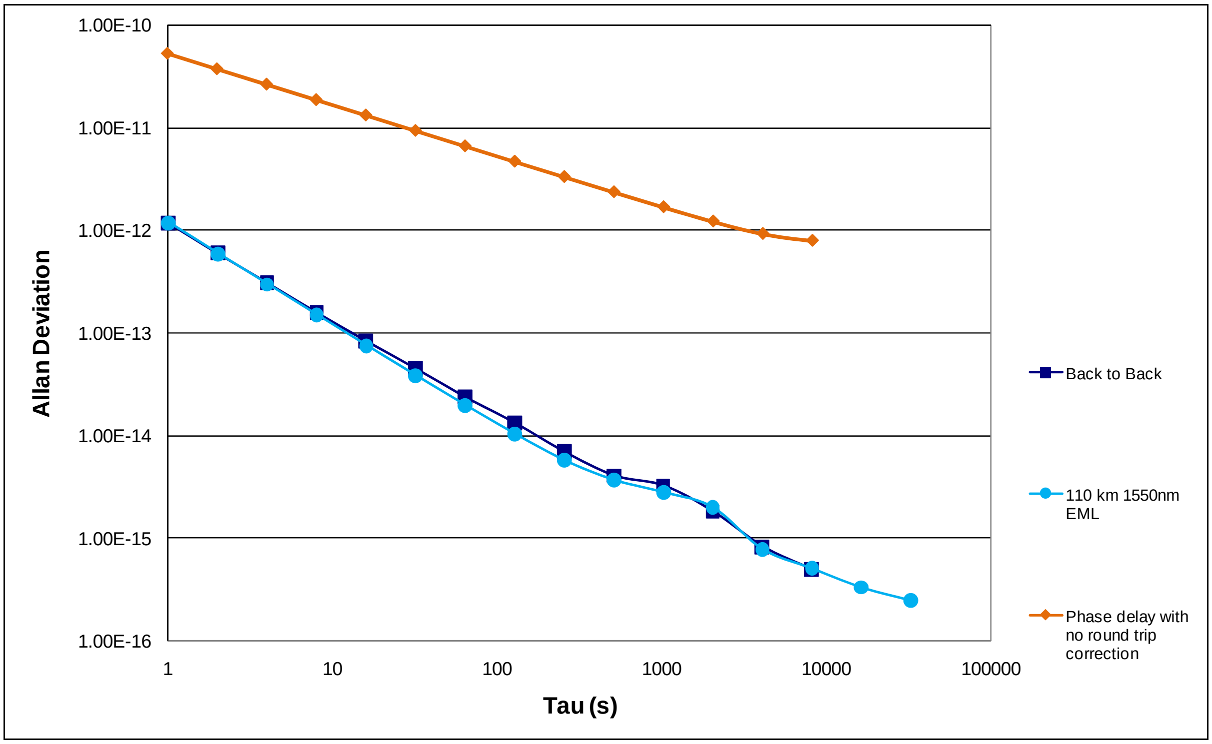

Figure 3. Allan deviation plot comparing: (1) a Back to Back measurement (2) a measurement using thermally controlled EMLs at 1550 nm and a 110-km fiber link and (3) a one-way transfer of an LO phase signal over 110 km with no round-trip correction .

The rms phase stability of a link of 110 km of installed fiber using thermally controlled lasers is:

- a 1 ps stability over 1 second
- a 1 ps stability over 1 minute,
- a 2 ps stability over 10 minutes, and
- a 4 ps stability over 2 hours.

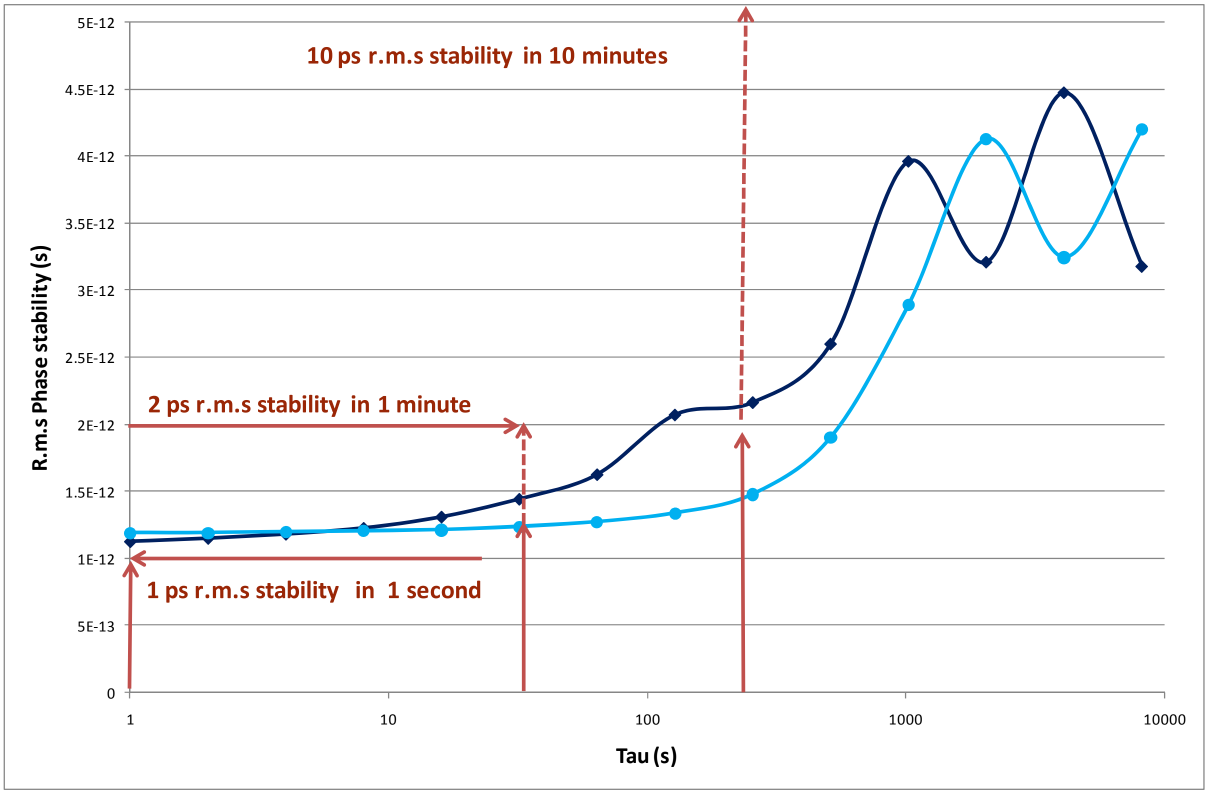

Figure 4. Rms phase stability measured using a Back to Back system and a 110-km fiber link, and comparison with system requirement specifications.

CONCLUSIONS

These results indicate that a round-trip correction system using commercially available, thermally controlled lasers, at 1550-nm wavelengths can achieve stabilities consistent with the requirements of radio astronomy at 22 GHz. Rms stabilities, as calculated from the measured values, are compared with the system requirements in Table 1 below.

In summary:

- Round-trip correction systems are essential for a radio astronomy at 22 GHz.
- Required stabilities can be achieved using an LBL over-fiber system.
- For long links, thermally controlled externally modulated 1550-nm lasers are recommended.

Table 1. Rms stability of an LBL over-fiber system using commercially available EMLs.

	Requirements Specifications	**Back to Back stability measured using only terminal equipment, no optics**	**Stability of a 1550-nm laser with thermal control over 110 km of fiber**
1 s	1 *ps rms*	1 *ps rms*	1 *ps rms*
1 min	2 *ps rms*	2 *ps rms*	1 *ps rms*
10 min	10 *ps rms*	3 *ps rms*	2 *ps rms*
2 hours	*As stable as possible*	3 *ps rms*	4 *ps rms*

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